CHARACTERISTICS OF ATMOSPHERIC FORCING FUNCTIONS

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THESIS

CHARACTERISTICS OF ATMOSPHERIC FORCING FUNCTIONS

by

Sharon Dill Raney

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Characteristics of Atmospheric Forcing Functions

by

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B.S., California State Polytechnic College, 1964

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requirements for the degree of

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The hypothesis that both the timing and magnitude of strong and weak atmospheric forcing events can have a significant effect on the seasonal evolution of the upper ocean thermal structure is investigated. Long time series of observations of meteorological data from ocean weather ships P, V, and N in the north Pacific Ocean are used to summarize the characteristics of the atmospheric forcing and the ocean thermal response during the January to August period. The forcing is expressed in terms of u_*^3, where u_* is the atmospheric friction velocity, and in terms of the upward heat flux. Although the total input of the three-hourly u_*^3 is quite different at all three stations, about 20% of the largest u_*^3 values contribute 50% of the accumulated u_*^3 and 50% account for 17% of the total at each station. Synoptic forcing events are defined as sustained periods during which the daily mean forcing exceeds the long-term mean. Between 68 and 75% of the total u_*^3 occurs during roughly one-third of the time associated with synoptic forcing events defined in terms of u_*^3. A significant fraction of the sea-surface temperature increase occurs during periods of low wind speed, rather than periods of excessive insolation.

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I. INTRODUCTION

The objective of this study was to examine the role of atmospheric forcing events in the modification of the upper ocean thermal structure during the late winter and summer seasons. The role of strong atmospheric forcing events in the modification of the upper ocean thermal structure during the cooling season was examined by Camp (1976). Simpson (1969) has demonstrated that significant air-sea exchanges (heat, moisture, and momentum) in mid-latitudes are concentrated almost entirely into synoptic scale forcing events. Simpson's analysis did not consider the response of the upper ocean to these large heat and energy fluxes. Camp's analysis concluded that a major fraction of the oceanic thermal structure modification between September and December occurred during periods of strong atmospheric forcing. These responses were largely one-dimensional and were principally the result of mechanical mixing and convective adjustment of the upper layers. Consequently, the atmospheric forcing is expressed in terms of u_*^3 (turbulent kinetic energy) and Q_n (net cooling where $Q_n = Q_a - Q_s$, Q_a is the upward heat flux and Q_s is the solar insolation) since these parameters are of primary significance in the formulation of non-advective mixed layer theory.

In this study the role of atmospheric forcing events in the January to August period was examined to test the hypothesis that storm forcing (or lack of it) during the warming season accounts for a major fraction of the oceanic thermal structure. An attempt was made to quantify decreases in sea-surface temperature during periods

of strong forcing and increases during weak forcing during this period at the end of the cooling season and throughout the warming season. Long term series of meteorological observations from ocean weather stations Papa (50N, 145W), November (30N, 140W), and Victor (34N, 164E) were used to infer the significant characteristics of the atmospheric forcing. Because the bathythermographs were taken irregularly, the ocean thermal response had to be inferred from the sea-surface temperature changes during periods of both strong and weak atmospheric forcing.

II. EQUATIONS FOR SURFACE FLUXES

Values of friction velocity (u_*) and upward heat flux (Q_a) are calculated from the meteorological observations at the ocean weather ships using standard bulk formulae (Paulson et al., 1972).

The friction velocity, in air, is calculated using the following formulas:

$$\tau_s = \rho_a C_D \bar{u}_a^2$$

$$u_* = (\tau_s/\rho_a)^{1/2}$$

where $\bar{u}_a$ is the mean wind speed (m/sec)

C_D is the non-dimensional drag coefficient (1.3×10^{3})

ρ_a is the density of air (1.25×10^{-3} gm/cm^3)

τ_s is the surface stress (dynes/cm^2)

The turbulent fluxes of latent heat (Q_e) and sensible heat (Q_h) are estimated using the following bulk aerodynamic formulas:

$$Q_e = C_D (.98\, E_s - E_a)\, \bar{u}_a$$

$$Q_h = C_D (T_s - T_a)\, \bar{u}_a$$

The net back radiation (Q_b) is estimated from the following empirical formula reported by Husby and Seckel (1975):

$$Q_b = 1.14 \times 10^{-7}\, (273.16 + T_s)^4 (.39 - .05 E_a^{1/2})(1. - .6C^2)$$

where E_s is the saturated vapor pressure of the marine air directly in contact with the sea surface (.98 corrects for salt defects)

E_a is the vapor pressure of air at approximately 10 m based on dew point temperature

T_a is the air temperature (degrees Centigrade)

T_s is the sea-surface temperature (degrees Centigrade)

C is the fractional cloud cover

The upward heat flux is then: $Q_a = Q_e + Q_h + Q_b$

The solar insolation, Q_s, was estimated by:

$$Q_s = (1. - a\alpha^b)\ (1. - .66C^3)\ Q_0$$

The constants a and b are adapted from Tabata (1964) and the cubic cloud cover correction from Laevastu (1960). The coefficient C is the fractional cloud cover and α is the mid-day elevation angle of the sun. The clear sky radiation, Q_0, is given by

$$Q_0 = A_0 + A_1\cos\phi + B_1\sin\phi + A_2\cos 2\phi + B_2\sin 2\phi$$

from the formula developed by Seckel and Beaudry (1973). The coefficients (A_0, etc.) were calculated by harmonic representation of the values presented in the Smithsonian Meteorological Tables (List, 1958) with $\phi = \frac{2\pi}{365}(t-21)$ where t is the julian day of the year.

Near surface marine observations at OWS P, V, and N were provided by the National Weather Records Center. This included 22, 22, and 15 years at OWS P (1949-1970), OWS N (1947-1970 except 1952 and 1953), and OWS V (1956-1970), respectively. The data were analyzed in two four-month periods, January to April and May to August. The September to December period was previously analyzed by Camp (1976). Other

related studies at these stations included Dorman (1974) who examined the spectral variation of heat fluxes at OWS N; Husby and Seckel (1975) who examined heat fluxes at OWS V; and Tabata (1964) at OWS P.

III. EFFECTS OF ATMOSPHERIC FORCING EVENTS ON THE SEASONAL EVOLUTION OF THE MIXED LAYER

Examples of the distributions of the mechanical generation of turbulent kinetic energy (u_*^3), convective generation of turbulent kinetic energy (Q_a) and solar insolation (Q_s) values at OWS V during the January to April 1959 period are shown in Figure III-1. An example from the May to August 1959 period is shown in Figure III-2. All of the long-term mean values used in this study were smoothed using a seven-point running mean. Both the long-term mean values and the daily mean values of u_*^3 for the early period are shown in Figure III-1d. The long-term mean decreased by about two-thirds during the period with the daily mean u_*^3 values having large variations about the long-term mean. The periods when the daily mean values exceed the long-term mean are defined as "events". In the case of u_*^3 exceeding the long-term mean, these events are referred to as "mechanical events". A corresponding variability with a period of a few days is also evident in the solar insolation (Q_s) and the upward heat flux (Q_a) shown in Figure III-1c. Variations in the insolation tend to increase as the available insolation increases toward the vernal equinox. In this example much of the upward heat flux variability is due to the wind speed since the heat flux peaks tend to coincide with the u_*^3 peaks.

The response, in terms of the sea-surface temperature and mixed layer depth, to this forcing is shown in Figures III-1a and III-1b. In Figure III-1d, one can see that February was a period of relatively weak forcing (the u_*^3 forcing was consistently below the long-term mean.)

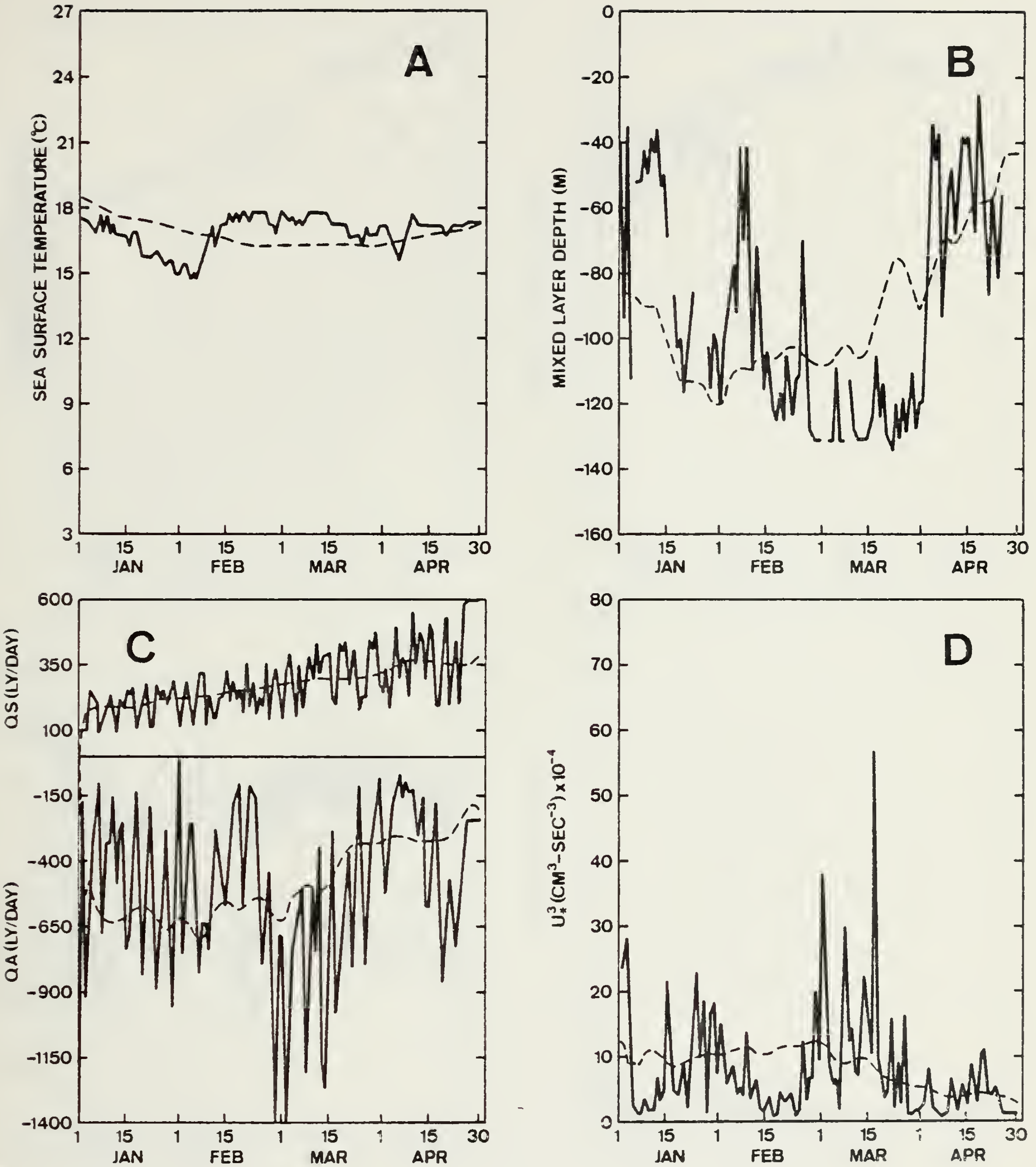

Figure III-1. Daily averaged values of a) sea-surface temperature, b) mixed layer depth, c) solar insolation and surface heat flux plus back radiation, and d) turbulent kinetic energy flux at OWS V during the January to April period of 1959. Dashed lines represent the long-term mean values.

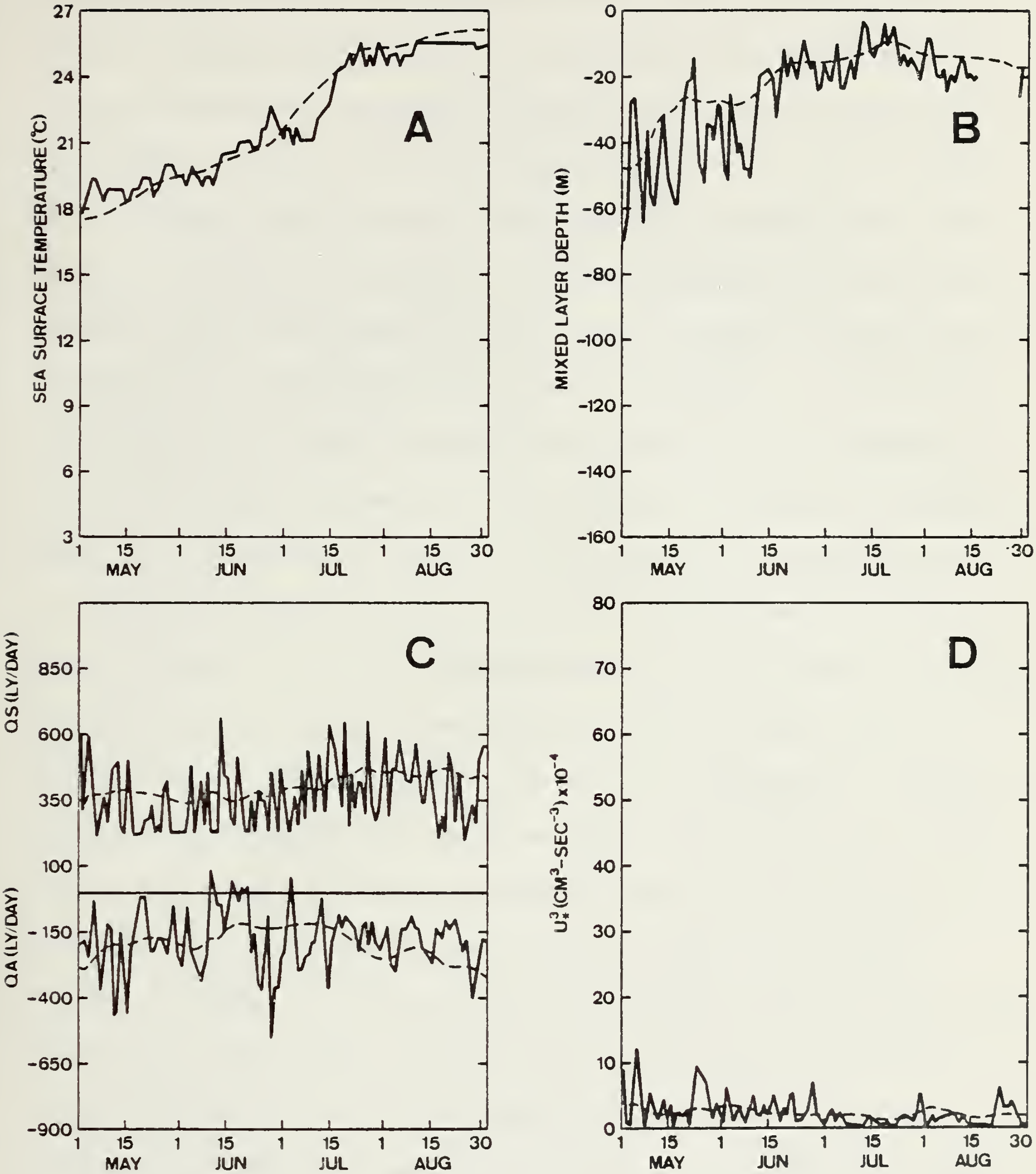

Figure III-2. Daily averaged values of a) sea-surface temperature, b) mixed layer depth, c) solar insolation and surface heat flux plus back radiation and d) turbulent kinetic energy flux at OWS V during the May to August period in 1959. Dashed lines represent the long-term mean values.

The sea-surface temperature response to this lack of strong forcing was quite dramatic during the first few weeks of February with a resulting temperature increase of nearly 3° C. Once the strong forcing resumed, the sea-surface temperature tended to decrease by about 2° C. Although the mixed layer depth was quite variable until late February, the period of strong forcing and upward heat fluxes during the next three weeks caused the mixed layer to deepen and tend to remain deep until the forcing diminished in late March. In this case the strong forcing acted to maintain the deep mixed layer throughout the period rather than cause further deepening. Retreat of the mixed layer is quite evident at the end of this period of strong forcing.

The distributions of u_*^3, Q_a, and Q_s for the summer period are shown in Figure III-2. The long-term mean value of u_*^3 again decreased during the period and had a magnitude much smaller than during the earlier period. The upward heat flux (Q_a) was considerably less than normal during this period. The mixed layer depth tended to be highly responsive to short periods of strong forcing during May and early June with rapid deepening during forcing and rapid retreat when forcing diminished. The beginning of July marked a period of low wind speed (e.g., the u_*^3 was less than the long-term mean). The mixed layer depth variability then decreased and the depth of the warm surface layer tended to remain fairly constant. The sea-surface temperature response to this period of weak forcing was a rapid increase of about 5° C. Once the stronger forcing resumed in August the sea-surface temperature tended to remain fairly constant.

These examples tend to support the hypothesis that significant ocean thermal responses occur in association with limited periods of both strong atmospheric forcing and weak atmospheric forcing.

Because advection may have had some effect on the ocean thermal response during individual periods, the statistical comparisons over a long period of time may have more significance than single event comparisons.

IV. CHARACTERISTICS OF THE THREE-HOURLY ATMOSPHERIC FORCING

Histograms of the friction velocity and of the terms related to the mechanical (u_*^3) and convective (Q_a) generation of turbulent kinetic energy are shown in Figures IV-1 to IV-3. These histograms are based on a ranking in order of increasing magnitude for all available three-hourly observations during the 22, 22, and 15 year periods at OWS P, N, and V, respectively. About 92% of all possible reports for the January to April period (94% for the May to August period) are included in the case of wind information, and about 75% for the Q_a values, because humidity measurements were missing more frequently. Mean values of u_* were .4, .36, and .26 ms^{-1} for the January to April period, and .29, .23, and .22 ms^{-1} for the May to August period at OWS P, V, and N, respectively. These values are consistent with the values (.42, .30, and .23 ms^{-1}) for the September to December period (Camp, 1976) and the distribution of westerly surface winds with latitude. OWS N tends to lie within the subtropical high pressure circulation with only moderate winds and few extreme values. By contrast, OWS P is affected by the passage of intense extratropical cyclones. Consequently, the u_*^3 values are distributed over a much larger range at OWS P than at N. The mean u_*^3 values were .11, .08, and .03 m^3s^{-3} at P, V, and N for the January to April period (.046, .024, and .017 m^3s^{-3} for the May to August period), respectively, which indicates a much different rate of turbulent kinetic energy production at the three locations. The mean values for the early period include the last two

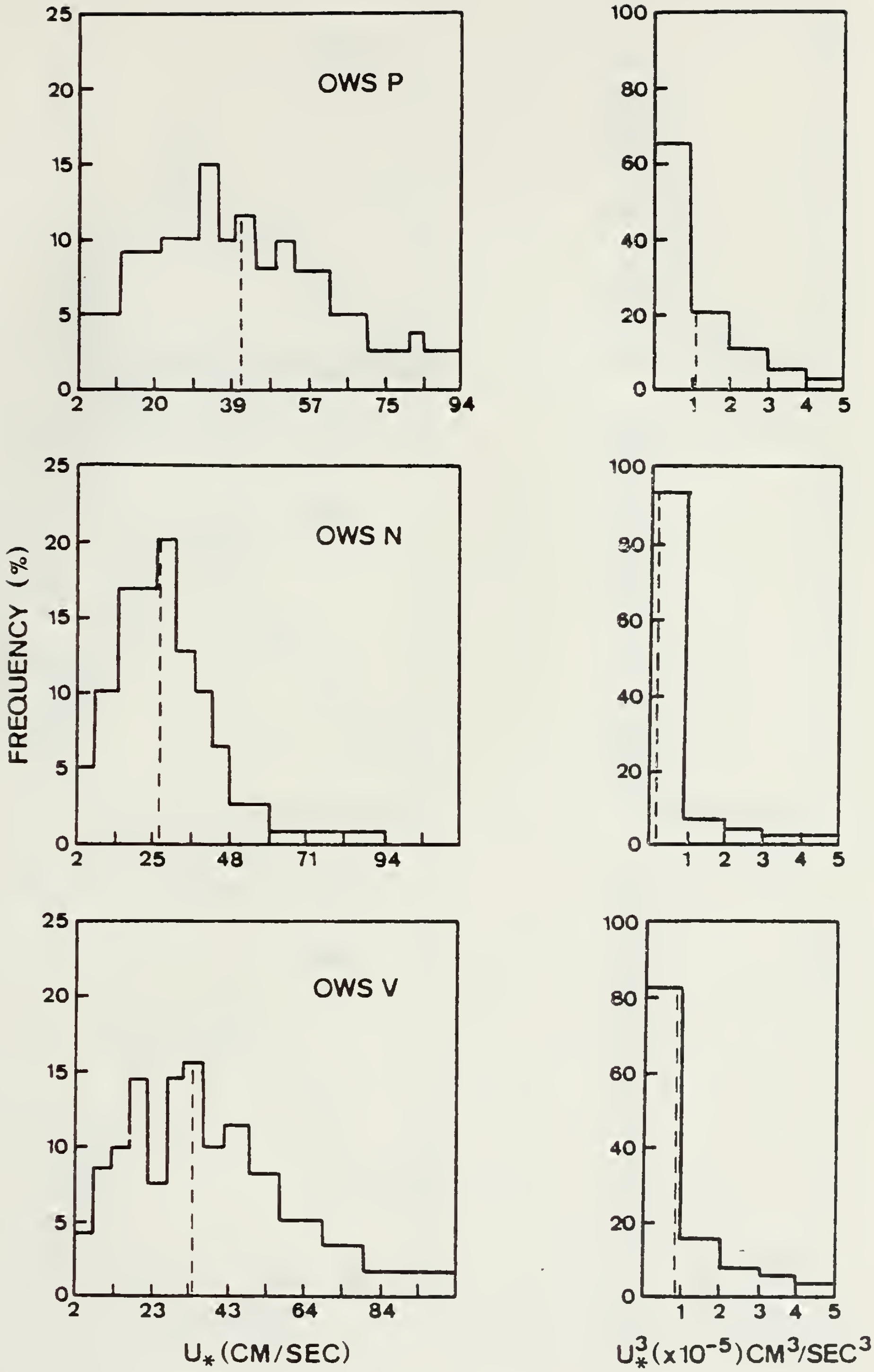

Figure IV-1. Histograms of u_* and u_*^3 from the three-hourly observations at OWS P, OWS N, and OWS V for the January to April period. Vertical dashed lines represent the mean of the distribution. Note that the abscissa for the OWS N u_*^3 distribution has been multiplied by 10^{-4} vs 10^{-5}.

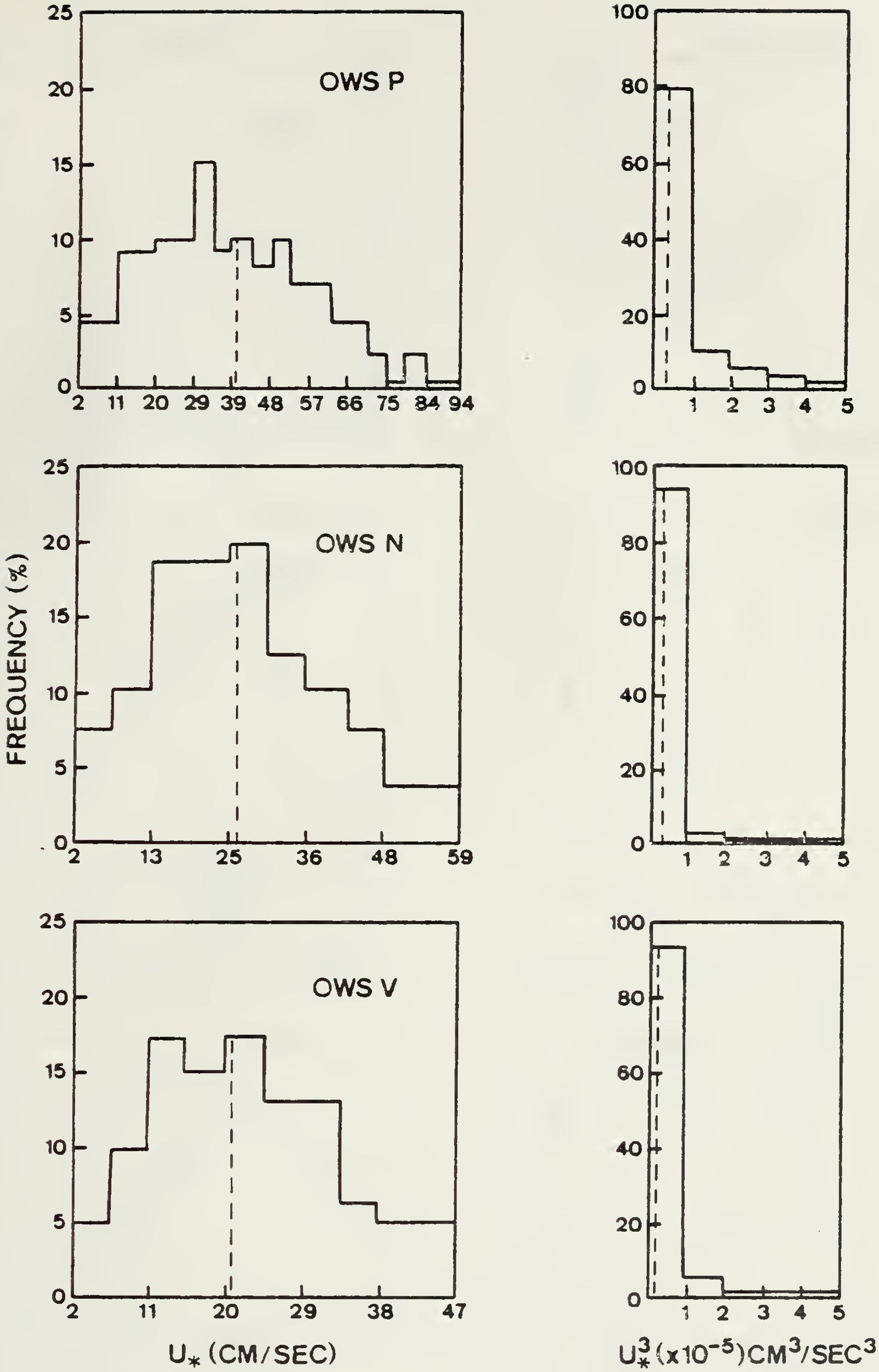

Figure IV-2. Histograms of u_* and u_*^3 from the three-hourly observations at OWS P, OWS N, and OWS V for the May to August period. Vertical dashed lines represent the mean of the distribution.

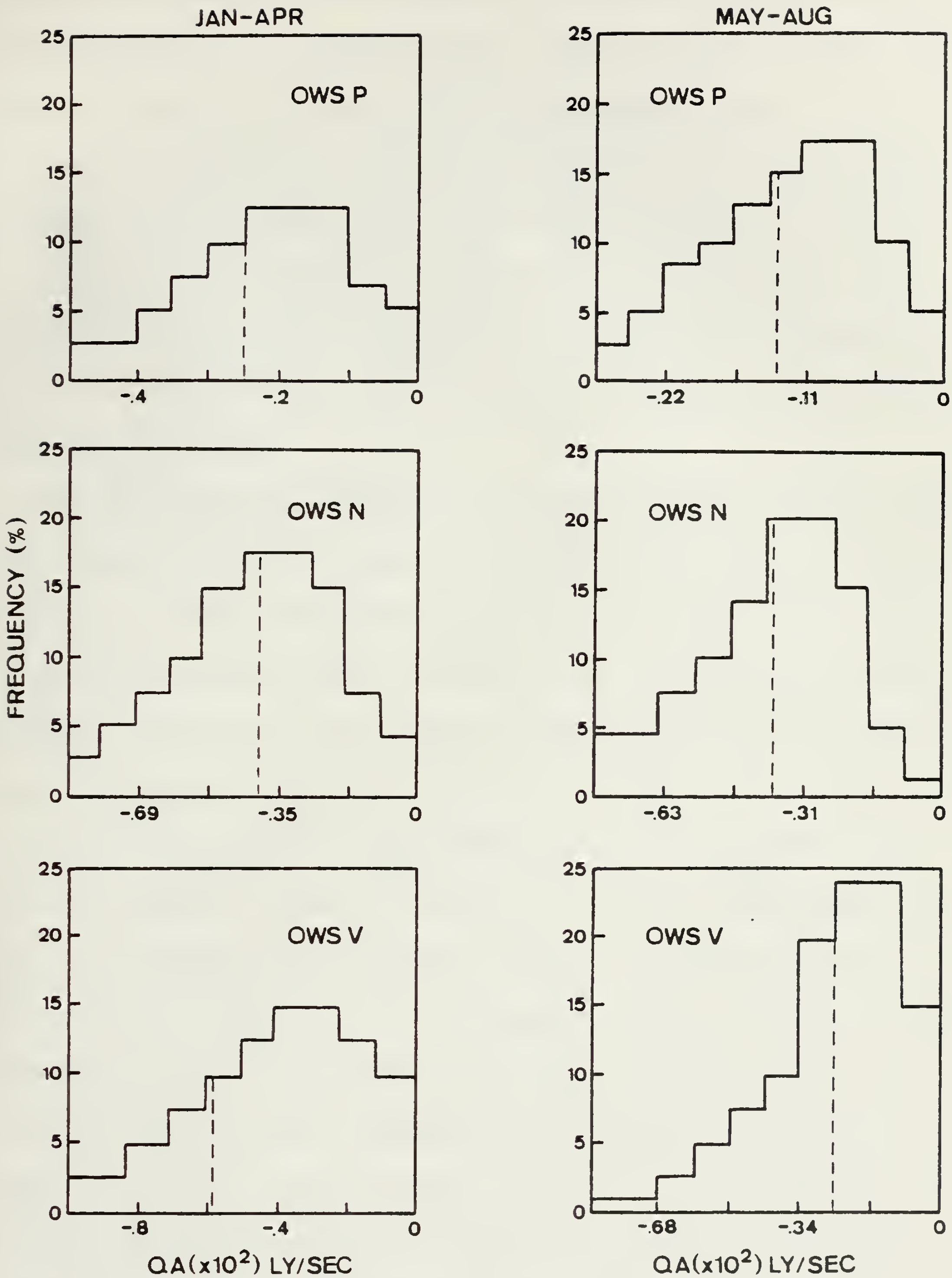

Figure IV-3. Histograms of surface heat flux plus back radiation for the January to April and May to August periods for OWS P, OWS N, and OWS V. Vertical dashed lines represent the mean of the distribution.

months of the cooling season (January and February) as well as the first two months of the warming season (March and April) which cause them to reflect much higher means than the summer period.

Consistent with the statistical characteristics of the September to December period (Camp, 1976), the standard deviation of the u_* at all stations for both periods is about one-half of the mean value. The standard deviation of the u_*^3 at all stations for both periods is at least one and one-half times the mean and at most two and one-half times the mean value.

The upward heat flux (Figure IV-3) is also skewed relative to the mean values of -.25, -.57, and -.42 ($\times 10^{-2}$) ly s^{-1} at P, V, and N, for the January to April period and -.14, -.25, and -.36 ($\times 10^{-2}$) ly s^{-1} for the May to August period. A majority of the Q_a values lie below these mean values with a few larger values accounting for the remaining flux. Although the larger variations in wind speed occur at P, the heat flux is larger at N. The variability of the atmospheric and oceanic parameters is shown in Table IV-1. Monthly mean sea-air temperature differences at P are about .25° C in January and .06° C in March (-.25° C in May and -.07° C in August). The corresponding mean vapor pressure differences are 1.1 and 1.2 mb (1.0 and 1.5 mb). By contrast the mean sea-air temperature differences at V are 2.6° C in January and 1.2° C in April (.64° C in May and .4° C in August) with corresponding vapor pressure differences of 7.7 and 4.9 mb (3.9 and 6.4 mb). At OWS N, the atmospheric parameters tend to remain fairly constant with very little variation. Average wind speed, sea-air temperature differences, and vapor pressure differences are 7.3 ms^{-1}, 1.3° C, and 6.6 mb for the January to April period and 6 ms^{-1}, 0.9° C,

Table IV-Ia

Variability of Atmospheric and Oceanic Parameters at OWS P

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug
u_a(m/sec)	11.8	11.6	11.0	10.2	8.9	8.2	7.2	8.1
$T_w - T_a$(°C)	.25	.03	.17	.06	-.23	-.32	-.23	-.07
$E_w - E_a$(mb)	1.1	.96	1.1	1.2	1.0	.9	.9	1.5

Table IV-Ib

Variability of Atmospheric and Oceanic Parameters at OWS V

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug
u_a	10.7	11.2	9.9	7.8	6.9	6.5	6.0	6.0
$T_w - T_a$	2.6	2.5	2.0	1.2	.64	.24	.005	.4
$E_w - E_a$	7.7	7.0	6.1	4.9	3.9	3.3	3.7	6.4

Table IV-Ic

Variability of Atmospheric and Oceanic Parameters at OWS N

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug
u_a	7.8	7.8	6.8	6.6	5.9	6.0	6.2	5.8
$T_w - T_a$	1.2	1.3	1.4	1.4	1.1	.9	.75	.73
$E_w - E_a$	6.2	6.2	6.9	6.9	6.8	6.7	6.8	7.5

and 7 mb for the May to August period. The mean of the Q_a distribution at N is approximately double its standard deviation while at OWS P and V the distribution of Q_a has more variance than the distribution of u_*. This implies that the variability of the turbulent heat flux is more closely coupled with the wind at OWS N than at the other stations. The increased variance in Q_a at OWS P and V is the result of a larger variability in the sea-air temperature and vapor pressure differences.

The total mechanical and convective generation of turbulent kinetic energy is related to the summation of the u_*^3 and Q_a distributions, respectively. The cumulative percentages of u_*^3, Q_a, and u_* plotted against the cumulative percentages of observations are shown in Figures IV-4 and IV-5. These curves are consistent with those obtained for the September to December period (Camp, 1976). For both periods, about 80% of the smallest u_*^3 values must be summed to contribute 50% of the accumulated u_*^3 which implies that the 20% consisting of the largest u_*^3 values contribute the remaining 50% of the total u_*^3. This demonstrates the importance of a few large events in the mechanical production of turbulent kinetic energy, and is consistent with the characteristic deepening of the mixed layer during periods of strong forcing. Also note that for both periods, about 50% of the observations account for about 17% of the accumulated u_*^3. These low wind speeds have an effect opposite that of the strong forcing, and it will be shown that they are important factors in the rapid warming of the upper ocean. The difference between the u_*^3 curve for the September to December period and the other two periods is due to the relative lack of extremely strong values of u_*^3 in the January to April and May to August periods.

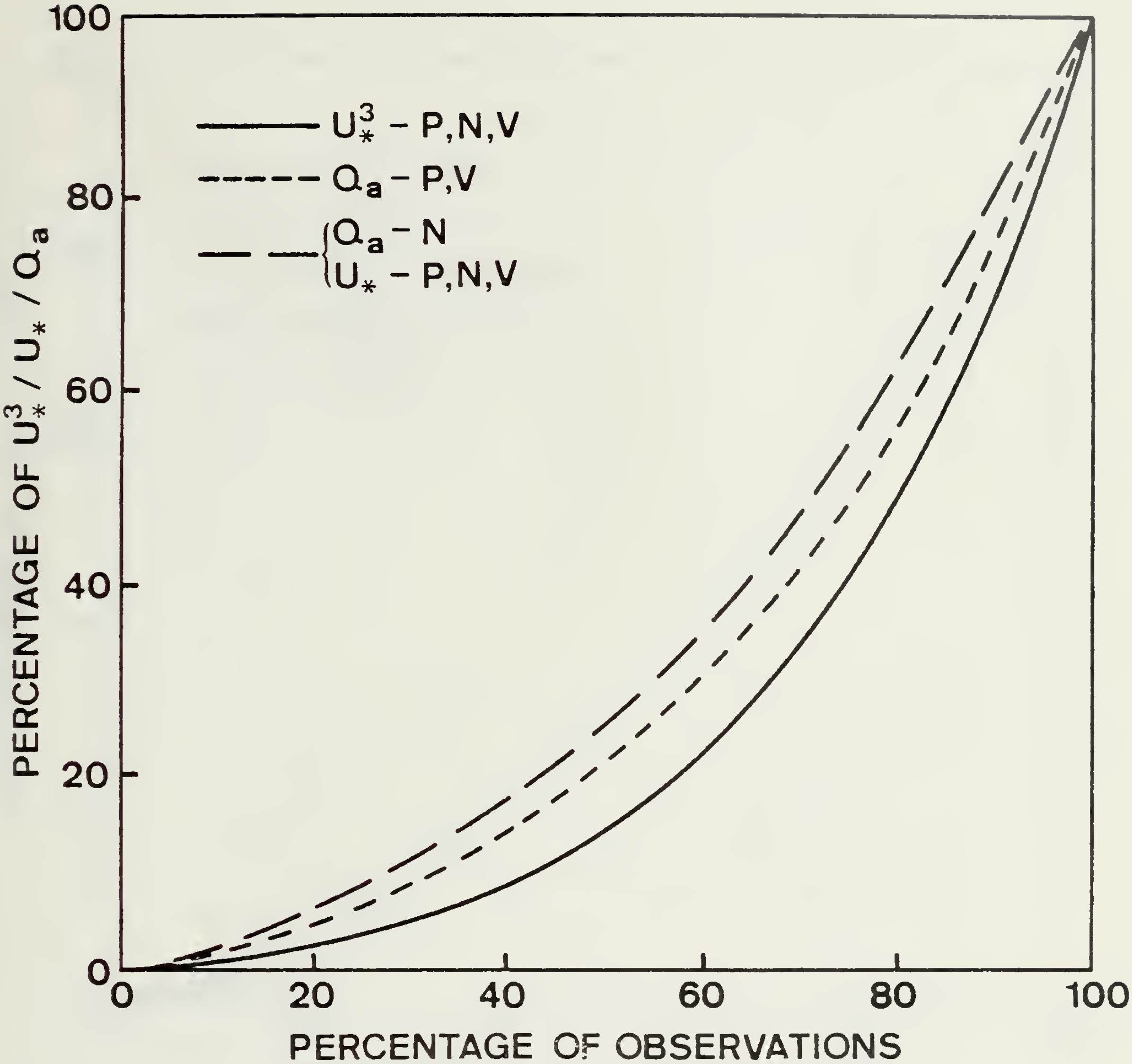

Figure IV-4. Cumulative percentage of rank-ordered three-hourly u_*, u_*^3, and Q_a values versus cumulative percentage of observations for the January to April period.

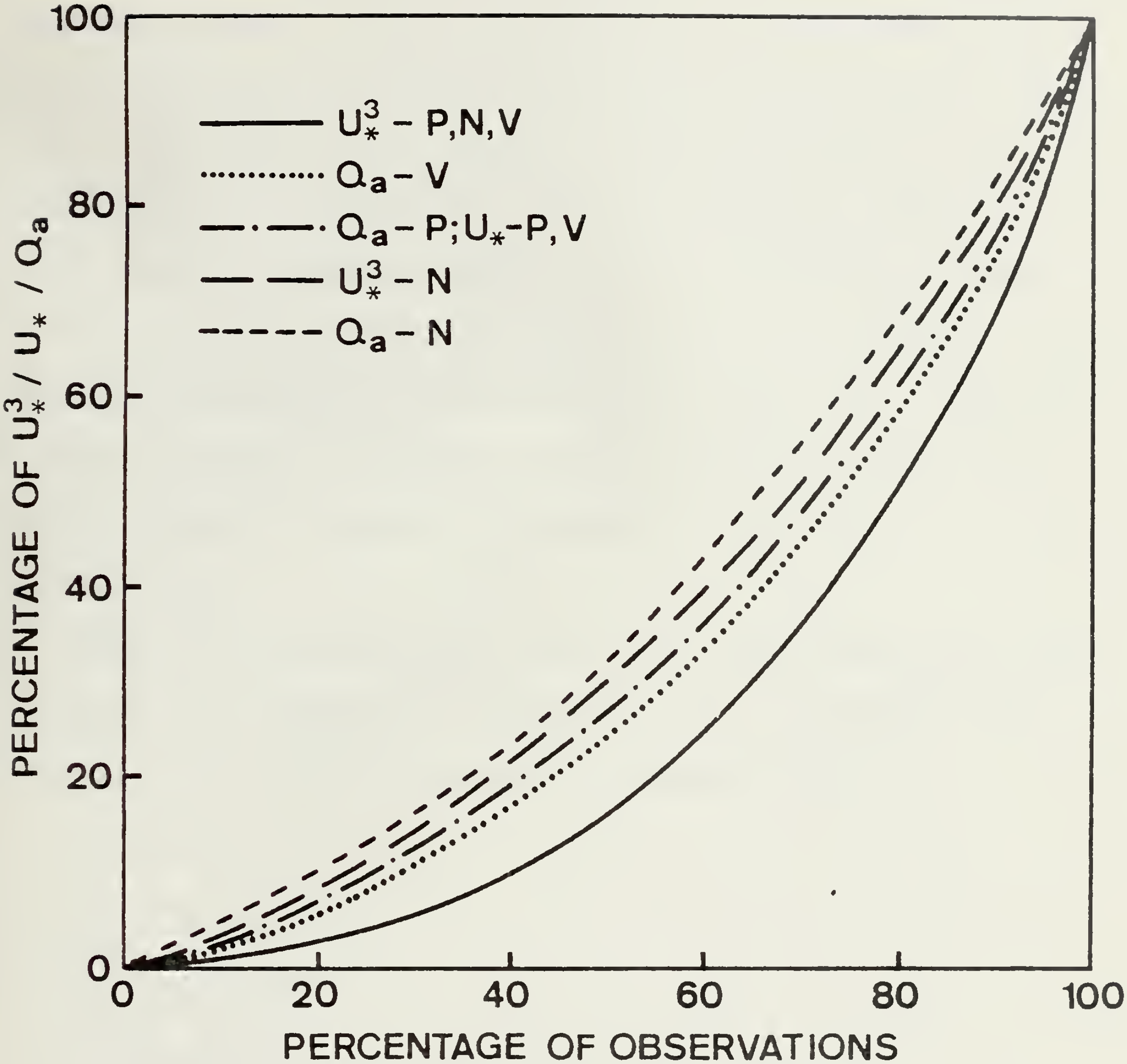

Figure IV-5. Cumulative percentage of rank-ordered three-hourly u_*, u_*^3, and Q_a values versus cumulative percentage of observations for the May to August period.

Although the total input of u_* and u_*^3 is quite different at the three stations, and during both four month periods, the uniformity of the distributions is consistent with that found during the September to December period. The Q_a distribution at N follows the u_* distribution in the early period and is quite similar in the summer period. This is consistent with the assumption that the variability of Q_a is associated with the wind speed rather than the sea-air temperature or vapor pressure differences at OWS N. The Q_a distributions at OWS P and V are also similar and lie between u_* and u_*^3 distributions. About 50% of the accumulated Q_a is associated with about 74% of the smallest Q_a fluxes for each of the three periods. The remaining 26% of the largest three-hourly values of Q_a account for the other half of the accumulated Q_a.

These relationships indicate that a significant percentage of the turbulent kinetic energy and surface heat flux is exchanged during relatively short periods of anomalous atmospheric forcing.

V. CHARACTERISTICS OF THE SYNOPTIC EVENT ATMOSPHERIC FORCING

In the previous section the three-hourly observations of u_*^3 and Q_a were ranked according to magnitude, so that similar values may have occurred in different years. In this section, the synoptic time series of u_*^3, Q_a, and Q_s will be examined to test the hypothesis that the presence or absence of a few periods of strong forcing can have a significant effect on the upper oceanic thermal structure.

Sustained periods of strong forcing (periods with u_*^3 values above the long-term mean forcing) and weak forcing (periods with u_*^3 values below the long-term mean) are defined as "mechanical events" and "low wind speed events", respectively. Sustained periods of upward heat flux with values less than the long-term mean upward heat flux are defined as "cooling events". Similarly, "heating events" are periods in which the solar insolation exceeds the long-term mean insolation. The objectives of this analysis were to examine the principal characteristics of these synoptic events, calculate the total energy exchange during these events and infer the oceanic response in terms of the sea-surface temperature change during these events.

An "event" as defined by Camp (1976) is the period of one day or more during which the daily mean value exceeds the long-term mean value for the day for the mechanical production of turbulent kinetic energy. Analogous definitions are used for the solar insolation, the upward heat flux, and the low wind speed periods. When an event begins in one month and ends in another, the event is credited to the month in which the largest fraction of the total energy flux occurred. It can be noted that the maximum u_*^3 value during a mechanical event may just exceed the long-term mean value, or the peak value may be many

times the mean value. This is also true in the case of heating events. The peak values of cooling events are negative and may be slightly less than the mean or many times less than the mean value. A low wind speed event is defined as the period during which the daily mean u_*^3 remains below the prescribed peak-to-mean ratio. Thus, events are also characterized in terms of their peak-to-mean ratios. The durations of the events, the magnitudes of the various fluxes and the sea-surface temperature changes which occur during each event are also calculated and accumulated.

A summary of the characteristics of the mechanical and heating events with peak values exceeding the long-term mean and the cooling and low wind speed events with peak values less than the long-term mean for the January to April and May to August periods are presented in Tables V-1 through V-4. A similar summary for the mechanical and heating events with peak values exceeding the long-term mean by a factor of at least 1.5 (and the cooling and wind speed events with peak values less than the long-term mean by a factor of at least 1.5) are shown in Tables V-5 through V-8. One of the most consistent results for both the seasonal totals, as in Tables V-1 and V-2, and the monthly values (to be presented later in this section) is the duration of the events. At each of the three stations, for both periods, about one-third of each period is affected by mechanical events. This same result was found in the study of the September to December period. The cooling events tended to last somewhat longer because the larger air-sea temperature differences persist longer than the wind speed peaks. One can see in Tables V-1 and V-2 that roughly 68 to 75% of the total u_*^3 occurred during roughly one-third of the time that mechanical events occurred. These statistics

Table V-1.

Characteristic Monthly Forcing and Response during Mechanical and Cooling Events with Peak-to-mean Ratios Greater than 1.0 for the January to April period.

Variable	Mechanical Events			Cooling Events		
	OWS P	OWS V	OWS N	OWS P	OWS V	OWS N
Duration (%)	36	36	34	45	45	43
u_*^3 (%)	70	68	72	57	60	62
Q_n (%)	78	64	89	152	101	135
Q_s (%)	39	48	35	54	47	47
Δ SST (%)	248	188	165	251	243	200
Number events/month	4.7	5.3	4.0	4.4	5.1	3.9
Duration of events (mean)	2.3	2.1	2.6	3.1	2.7	3.4
Peak-to-mean ratio	1.8	1.8	1.9	1.5	1.4	1.3

Table V-2.

Characteristic Monthly Forcing and Response during Mechanical and Cooling Events with Peak-to-mean Ratios Greater than 1.0 for the May to August period.

Variable	Mechanical Events			Cooling Events		
	OWS P	OWS V	OWS N	OWS P	OWS V	OWS N
Duration (%)	37	35	38	50	44	47
u_*^3 (%)	75	73	74	56	54	72
Q_n (%)	37	25	7	47	26	8
Q_s (%)	38	32	36	57	47	46
ΔSST (%)	-19	-18	-36	31	5	-21
Number events/month	4.6	4.3	3.3	4.8	4.1	3.8
Duration of events (mean)	2.4	2.4	3.4	3.1	3.3	3.7
Peak-to-mean ratio	1.8	1.8	1.7	1.4	1.5	1.2

Table V-3.

Characteristic Monthly Forcing and Response during Heating and Low wind speed Events with Peak-to-mean Ratios Greater than 1.0 for the January to April period.

Variable	Heating Events			Low wind speed Events		
	OWS P	OWS V	OWS N	OWS P	OWS V	OWS N
Duration (%)	46	52	49	62	62	64
u_*^3 (%)	46	54	51	31	34	30
Q_n (%)	46	63	8	26	53	6
Q_s (%)	61	67	64	63	63	70
ΔSST (%)	81	91	-4	-148	-88	-65
Number events/month	6.4	6.8	6.3	4.8	5.3	4.1
Duration of events (mean)	2.1	2.3	2.4	3.9	3.5	4.7
Peak-to-mean ratio	1.3	1.3	1.3	x	x	x

Table V-4.

Characteristic Monthly Forcing and Response during Heating and Low wind speed Events with Peak-to-mean Ratios Greater than 1.0 for the May to August period.

Variable	Heating Events			Low wind speed Events		
	OWS P	OWS V	OWS N	OWS P	OWS V	OWS N
Duration (%)	39	49	52	64	67	63
u_*^3 (%)	41	40	46	28	31	29
Q_n (%)	53	71	95	67	81	100
Q_s (%)	52	64	66	66	73	69
ΔSST (%)	57	70	97	119	118	135
Number events/month	5.9	5.5	5.6	4.7	4.4	3.3
Duration of events (mean)	2.0	2.7	2.8	4.2	4.5	5.7
Peak-to-mean ratio	1.4	1.3	1.2	x	x	x

indicate the highly skewed nature of the turbulent kinetic energy generation, and also, that a significant fraction is associated with events having a synoptic time scale.

One can also note in Table V-I that periods of mechanical events are also periods of significant net cooling ($Q_n = Q_a - Q_s$) during the January to April period. Also, periods of upward heat flux less than the long-term mean account for 101 to 152% of the net heat flux during the January to April period at the three stations. The values exceeding 100% may be explained by noting that the intervals between events may be periods of downward heat flux. That is, the periods of upward heat flux associated with the events can account for more than the monthly or seasonal flux which includes both upward and downward heat flux periods.

The thermal response during the events was estimated from the daily mean sea-surface temperature. If, as was the normal case, all the three-hourly observations were available, the trend in the daily mean values was reasonably smooth. Because the net sea-surface temperature change during weak or short events may be small, the estimates may be subject to larger errors than for the accumulated u_*^3 or Q_a values described above. Long-term mean temperature decreases from the beginning of January to the end of April were .4, 1.1, and .76° C at OWS P, V, and N, respectively. These decreases were small because the sea-surface temperature during January and February decreases and then increases in March and April resulting in a net decrease for the overall period. The percentage of the seasonal sea-surface temperature change that occurred during the mechanical events for the early period ranged from 165% at OWS N to 248% at OWS P. Again the percentages greater than 100 can be explained by the fact that the events are associated with periods of sea-surface temperature decrease, while the long-term change includes both

increases and decreases. The values during cooling events for the same period were similar and ranged from 200% at OWS N to 215% at OWS P.

During the May to August period, the percentages of sea-surface temperature change during mechanical events (Table V-2) were quite small (-18% at OWS V to -36% at OWS N). The negative percentages were due to the fact that although the sea-surface temperature decreased during the mechanical events, the long-term sea-surface temperature change was positive for the period. Long-term mean temperature increases from the beginning of May to the end of August were 7.35, 8.65, and 4.16° C at OWS P, V, and N, respectively. The sea-surface temperature would have increased more had there been no high wind speed events to mix the water down. The sea-surface temperature change during the cooling events was similar and ranged from -21% at OWS N to 31% at OWS P. The positive sea-surface temperature changes at OWS P and V were due to reduced warming rather than cooling. During this period, the net cooling (Q_n) was quite small during both the mechanical and cooling events. During mechanical events 7% of the net cooling (Q_n) occurred at OWS N and 37% at OWS P while during the cooling events 8% occurred at OWS N and 47% occurred at OWS P. These results are consistent with the corresponding sea-surface temperature changes during the January to April period, but do not explain the small magnitude of the sea-surface temperature changes.

The frequency and duration of the mechanical and cooling events are shown in Tables V-1 and V-2 and tend to follow the pattern found in the September to December period. At OWS P there was an average of 4.7 mechanical events in the early period lasting 2.3 days each (4.6 in the summer lasting 2.4 days). At OWS N there was an average of 4.0 events in the early period with a longer duration of 2.6 days each (3.3 events

lasting 3.4 days in the summer period). The cooling events lasted longer than the mechanical events which is also consistent with the results for the September to December period. The average peak-to-mean ratio for the cooling events was 1.4 for both periods and 1.9 for the mechanical events, which is also true for the September to December period.

The objective when examining the mechanical and cooling events was to determine the source of the sea-surface cooling and mixed layer deepening. To determine the source of warming, particularly rapid warming, periods of excessive solar insolation (Q_s) were examined along with low wind speed periods during which warm water may not be being mixed downward. Examination of the heating events (Table V-3) for the January to April period shows that they occur approximately one-half of the time and about one-half of the total mechanical forcing occurs during these heating events. About two-thirds of the total solar insolation (Q_s) occurs during one-half of the time. Neither the net cooling (Q_n) nor the sea-surface temperature change show a significant trend during the heating events, because upward heat flux (Q_a) tends to offset the effect of the heating (Q_s). The heating events lasted about the same length of time as the mechanical events but were more numerous. At OWS P there was an average of 6.4 heating events in the early period lasting 2.1 days each (5.9 in the summer lasting 2.1 days each). At OWS N there was an average of 6.3 events in the early period lasting 2.4 days each (5.6 in the summer lasting 2.8 days each).

Finally the periods of low wind speed (weak forcing) are shown in Tables V-3 and V-4. As expected from the characteristics of the mechanical events in Tables V-1 and V-2, these weak forcing events occur about two-thirds of the time and account for approximately one-third of the

mechanical forcing. The net cooling (Q_n) during these low wind speed periods is small during the early period, when the overall sea-surface temperature decreased, and is significantly larger during the summer period when there was a large increase in the sea-surface temperature. The striking result is the consistently large percentage of sea-surface temperature change that occurred during both periods. The sea-surface temperature increased during all of the low wind speed events. In Tables V-3 and V-4, there was no evidence of anomalous heating (Q_s) during the low wind speed events. The amount of heating during these events is essentially the amount expected for that duration. Thus the warming of the sea-surface is not due to excessive Q_s but the small amount of u_*^3 which permits the heat to be concentrated in a small layer near the surface. This tends to strengthen the hypothesis that the sea-surface temperature change is related to the amount of wind available.

The low wind speed events lasted about twice as long as the mechanical events and about the same number occurred. At OWS P in the early period there was an average of 4.8 low wind speed events lasting 3.9 days each (4.7 events in the summer period lasting 4.2 days each). At OWS N, there was an average of 4.1 events in the early period lasting 4.7 days each (3.3 events in the summer period lasting 5.7 days each). In comparison to the heating events, there were fewer low wind speed events but they lasted almost twice as long.

The characteristics and the associated responses for events with peak-to-mean ratios of at least 1.5 are presented in Tables V-5 through V-8. The low wind speed events with peak-to-mean ratios greater than 1.5 presented in Tables V-7 and V-8 were not equivalent to the periods when mechanical events with peak-to-mean ratios greater than 1.5 did not occur.

Table V-5.

Characteristic Monthly Forcing and Response during Mechanical and Cooling Events with Peak-to-mean Ratios Greater than 1.5 for the January to April period.

Variable	Mechanical Events			Cooling Events		
	OWS P	OWS V	OWS N	OWS P	OWS V	OWS N
Duration (%)	21	24	21	19	17	11
u_*^3 (%)	45	48	49	30	26	19
Q_n (%)	50	42	62	89	50	49
Q_s (%)	23	24	21	21	15	12
Δ SST (%)	203	150	103	147	105	68
Number events/month	2.3	2.7	2.0	1.5	1.5	.73
Duration of events (mean)	2.7	2.6	3.2	4.0	3.3	4.6
Peak-to-mean ratio	2.4	2.3	2.6	1.9	1.9	1.9

Table V-6.

Characteristic Monthly Forcing and Response during Mechanical and Cooling Events with Peak-to-mean Ratios Greater than 1.5 for the May to August period.

Variable	Mechanical Events			Cooling Events		
	OWS P	OWS V	OWS N	OWS P	OWS V	OWS N
Duration (%)	23	20	20	19	17	6
u_*^3 (%)	49	46	43	27	26	10
Q_n (%)	23	13	2	17	5	-1
Q_s (%)	23	19	19	23	18	6
Δ SST (%)	-14	-14	-24	7	-2	-2
Number events/month	2.3	2.1	1.5	1.4	1.3	.3
Duration of events (mean)	2.9	2.9	4.1	4.2	3.9	5.8
Peak-to-mean ratio	2.5	2.5	2.4	1.8	2.1	1.8

Table V-7.

Characteristic Monthly Forcing and Response during Heating and Low wind speed Events with Peak-to-mean Ratios Greater than 1.5 for the January to April period.

Variable	Heating Events			Low wind speed Events		
	OWS P	OWS V	OWS N	OWS P	OWS V	OWS N
Duration (%)	12	6	3	66	68	69
u_*^3 (%)	11	3	3	37	41	36
Q_n (%)	6	-.3	-.8	28	61	15
Q_s (%)	17	10	4	70	69	75
Δ SST (%)	-11	-13	-27	-162	-128	-36
Number events/month	1.6	.55	.34	3.6	3.8	3.1
Duration of events (mean)	2.4	3.0	3.0	5.5	5.3	6.6
Peak-to-mean ratio	1.6	1.6	1.5	x	x	x

Table V-8.

Characteristic Monthly Forcing and Response during Heating and Low wind speed Events with Peak-to-mean Ratios Greater than 1.5 for the May to August period.

Variable	Heating Events			Low wind speed Events		
	OWS P	OWS V	OWS N	OWS P	OWS V	OWS N
Duration (%)	14	9	1	68	71	67
u_*^3 (%)	17	9	5	34	36	35
Q_n (%)	22	14	3	72	85	102
Q_s (%)	21	12	2	71	78	73
Δ SST (%)	20	19	4	122	122	130
Number events/month	1.8	.95	.13	3.7	3.6	2.7
Duration of events (mean)	2.3	2.9	2.9	5.5	6.4	7.5
Peak-to-mean ratio	1.8	1.6	1.5	x	x	x

The low wind speed events in these tables were defined as those periods in which the daily forcing was continuously less than one and one-half of the long-term mean forcing whereas the mechanical events were periods in which the <u>maximum</u> value of the daily forcing exceeded the long-term mean by a factor of 1.5 or more.

This selection process eliminated about one-half of the mechanical events and two-thirds of the cooling events that were included in Tables V-1 and V-2. Less than 15% of the heating events shown in Tables V-3 and V-4 remain. Stronger mechanical events were rare in the early period, as there was an average of 2.7 per month at OWS V and 2.0 at OWS N, and were even less frequent in the summer period, indicating a lack of extremely strong mechanical forcing during both periods. As in the September to December period, the average duration of the strong mechanical events with peak-to-mean ratios greater than 1.5 was longer than during the weaker events. Many of the weaker events were also very short and thus were eliminated in the selection process. In both periods about 48% of the total u_*^3 occurred during 22% of the time. The sea-surface temperature again decreased during mechanical events. The January to April sea-surface temperature changes ranged from 103% at OWS N to 203% at OWS P. The large percentages can be attributed to the fact that while the long-term mean temperature decreased during this period, the sea-surface temperature decrease during the events was larger than the mean seasonal decrease. The May to August sea-surface temperature changes ranged from -14% at OWS P and V to -24% at OWS N. In this case, the long-term mean increased by a considerable amount, but the sea-surface temperature changes during the events resulted in a net decrease during the mechanical events. The sea-surface temperature

changes during the low wind speed events were larger than those with a peak-to-mean ratio of 1.0. In addition, the overall percentage of time during which the low wind speed events occurred increased by about 4%. These two factors lead to the conclusion that more sea-surface temperature increases occurred during these longer events.

The overall seasonal statistics in Tables V-1 through V-4 were also divided into monthly periods for the 22, 15, and 22 years at OWS P, V, and N, respectively. The percent of time and the sea-surface temperature change during the mechanical, cooling, heating, and low wind speed events are summarized in Tables V-9 and V-10. One of the most important points is the relative invariance at each station in the percentage of time these events occurred during the January to August period. This same invariance can be found in the September to December period. In general, the mechanical events are shorter in duration than the cooling events and the heating events are about as long as the cooling events. However, the oceanic response to this essentially uniform frequency varies significantly through the year.

The largest percentage contribution to the oceanic response by the events occurs during March (except at OWS N where it occurs in April). March tends to be the transition month between the cooling and heating seasons, with the transition being progressively later at the equatorward stations. Thus, the net monthly sea-surface temperature changes in March are small.

The relatively large sea-surface temperature changes during low wind speed events in March and April were due to the fact that during these months the changes during the events were quite large but the net monthly sea-surface temperature changes were small. During the May to August

Table V-9. Percent of time and associated monthly sea-surface temperature change during mechanical (u_*^3) and cooling (Q_a) events

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug
				Mechanical events				
P: Time	36	37	37	36	36	42	35	36
Δ SST	69	38	-183	-74	-13	-23	-1	-77
V: Time	36	36	37	35	34	38	36	31
Δ SST	55	94	356	-26	-30	3	-5	-94
N: Time	34	37	34	30	34	42	39	38
Δ SST	47	70	-53	-311	-29	-37	-52	-28
				Cooling events				
P: Time	47	45	45	45	48	54	49	48
Δ SST	64	134	-316	-2	42	28	41	-15
V: Time	44	45	46	44	43	46	46	40
Δ SST	82	108	426	-30	17	2	24	-87
N: Time	41	46	44	41	42	52	44	50
Δ SST	76	124	4	-365	-19	-36	-31	-2

Table V-10. Percent of time and associated monthly sea-surface temperature change during low wind speed and heating (Q_s) events

	Jan	Feb	Mar	Apr	May	Aug	Jul	Aug
				Low wind speed events				
P: Time	60	63	63	61	61	69	65	64
Δ SST	31	62	283	174	113	123	101	177
V: Time	60	64	63	62	63	73	64	69
Δ SST	45	6	-256	-88	130	97	105	194
N: Time	62	63	66	66	60	68	62	62
Δ SST	53	30	153	410	130	137	146	129
				Heating events				
P: Time	45	46	47	49	41	38	36	38
Δ SST	61	71	47	44	57	64	54	48
V: Time	55	54	51	48	47	45	48	57
Δ SST	58	117	206	71	62	58	70	112
N: Time	49	50	48	49	48	54	51	55
Δ SST	44	44	69	300	71	116	105	102

period, the overall increase was more proportional to the increases during the events. The sea-surface temperature changes during the heating events at OWS P appear to be of minor significance. However at both OWS N and V, there is a high degree of variability from month to month indicating that some other factor (such as cooling or wind speed) controlled the sea-surface temperature changes during the heating events.

VI. SUMMARY

The three-hourly surface data from OWS P, V, and N have been examined to determine the contribution of atmospheric forcing to the changes in the ocean thermal structure between January and August. The forcing is specified in terms of non-advective mixed layer dynamics, which Camp (1976) has shown to be capable of explaining a major portion of the ocean thermal structure modification at three specific locations during periods of anomalous atmospheric forcing. The ocean thermal response was evaluated in terms of the changes of daily averaged sea-surface temperature.

Although the total generation of turbulent kinetic energy by mechanical (u_*^3) and thermal (Q_a) forcing is quite different at the three OWS locations the uniformity of the cumulative u_* and u_*^3 distributions at the three stations is quite remarkable. A very large percentage of that total forcing occurred during a relatively small fraction of the time at all stations and for all seasons. By ranking the three-hourly observations of u_*^3, it was demonstrated that about 20% of the largest u_*^3 values contribute 50% of the total u_*^3 at each station. Also 50% of the smaller u_*^3 values account for 17% of the accumulated u_*^3. The u_* and u_*^3 distributions are consistent with those of the September to December period studied by Camp (1976). A similar distribution of cooling (Q_a) is found at OWS P and V, but this thermal forcing is less skewed than the u_*^3 input. The variability in Q_a at OWS N tends to follow the u_* distribution, which suggests the variability of the sea-air temperature differences is less important at OWS N.

A synoptic forcing event was defined as the period during which the atmospheric forcing was greater than the long-term mean for the corresponding day. At OWS P there are typically 4.7 mechanical events lasting an average of 2.3 days in the January to April period and 4.6 events lasting 2.4 days in the May to August period. Although the total forcing is different at each station, 37%, 36%, and 34% of the time is associated with mechanical events at OWS P, V, and N, respectively, during the early season and 37%, 35%, and 38% of the time during the summer season. The important point is that between 68 and 75% of the total u_*^3 occurred during roughly one-third of the time associated with mechanical events during the January to August period. This is consistent with the results for the September to December cooling period which had significantly higher values of u_*^3. The events defined in terms of upward heat flux give a similar indication of the dominant role of synoptic-period systems in the mechanical and thermal forcing of the upper oceans. The low wind speed events which occurred about two-thirds of the time were associated with most of the sea-surface temperature increases. During these weak forcing periods, the sea-surface temperature changes ranged from -65% at N to -148 at P during the January to April period. In the summer, the percentages of sea-surface temperature changes ranged from 118% at P to 135% at N. Consequently the presence or absence of a few of these strong forcing events during a month or season can have a significant effect on the seasonal evolution of the mixed layer. Both the intensity and time of the synoptic period forcing is needed to understand and predict the seasonal evolution of the upper ocean thermal structure.

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